Constraining and understanding particle acceleration

Felix Spanier
Lehrstuhl für Astronomie
Universität Würzburg

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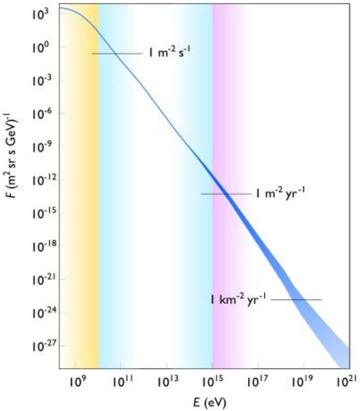
Cosmic rays

The paradigm for understanding the cosmic ray spectrum:

- Diffusive shock acceleration at SNR shock waves
- Energy-dependent propagation through the turbulent ISM
- At ultra-high energies sources must be extragalactic
- Active Galactic Nuclei are prime candidates
- Nonthermal particle distributions are associated with nonthermal radiation signatures

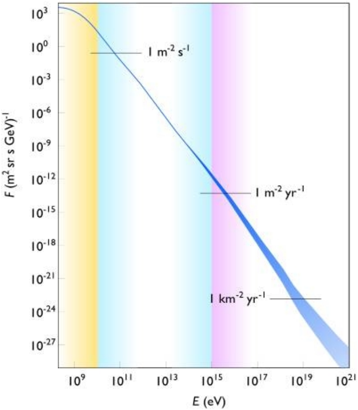


Cosmic rays

Open questions

- **How can we decipher UHE cosmic rays from their nonthermal emission spectra?**
- **Can we understand particle acceleration up to their extreme energies?**

Understanding augmented by numerical simulations



Acceleration mechanisms

Terrestrial accelerators

- Acceleration through electric fields
- Particle confinement is a major problem

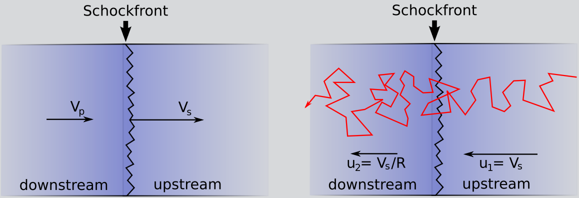
Cosmic accelerators

- Cosmic plasmas are conductive, no large scale electric field
- Low magnetic fields require large confinement volumes
- Blazars are highly variable and compact

Diffusive shock acceleration

Fermi-I – non-relativistic

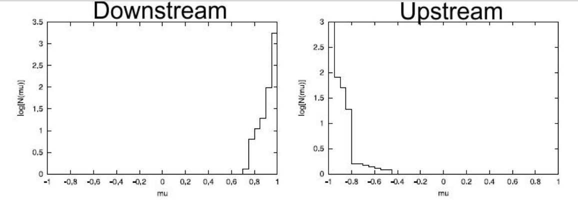
Multiple shock crossings
Compression ratio $r = u_u/u_d$ defines spectral index
($1 < r \leq 4$ non-relativistic)
Spectral index $s = \frac{r+2}{r-1}$



Diffusive shock acceleration

Fermi-I – relativistic

Again multiple shock crossings
Compression ratio $1 < r \leq 3$ relativistic
Relativistic shock: Anisotropic particle distribution ($s \approx 2.2$)

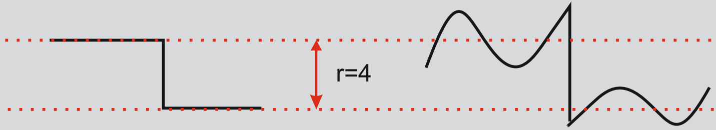


μ distribution, shock frame, $\Gamma = 200$ (Source: Meli & Quenby, 2003)
Anisotropy requires complicated simulations

Diffusive shock acceleration

Fermi-I beyond $s = 2$

Alfvén waves may increase the effective compression ratio (Vainio& Schlickeiser 1998)



Works well when the fluctuating amplitude is large compared to the background field (low Mach number)
Shock modification (Berezhko & Ellison 1999)

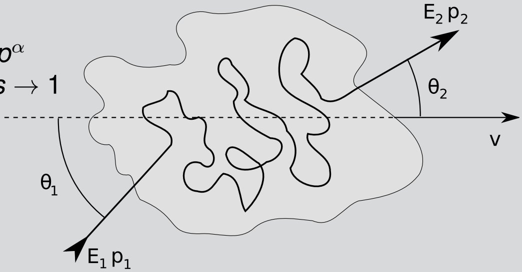
Diffusive shock acceleration

Fermi-II

Energy diffusion by stochastic scattering off Alfvén waves

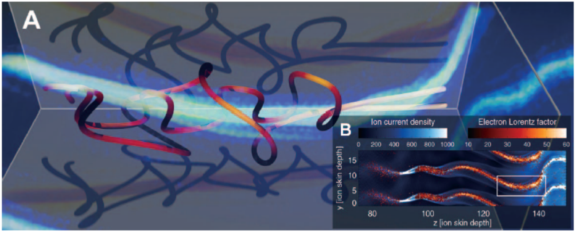
$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial}{\partial p}f\right)$$

Energy gain $\propto u^2/c^2$
Acceleration time $\propto c^2/v_A^2 p^\alpha$
Possibly flatter spectra to $s \to 1$
(Virtanen & Vainio, 2005)



Filamentation instability

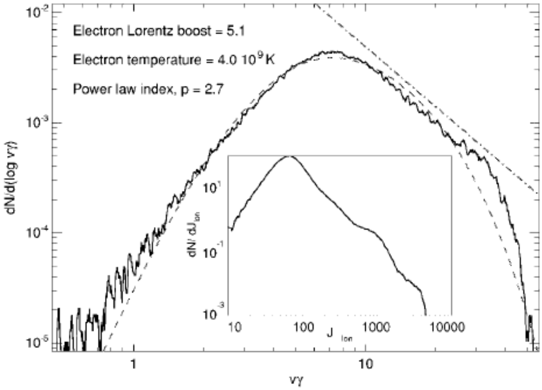
Since Hededal et al. (2004) filamentation / Weibel instability is discussed
Non-magnetized counterstreaming plasmas generate filaments



(Source: Hededal et al. 2004)

Novel mechanisms

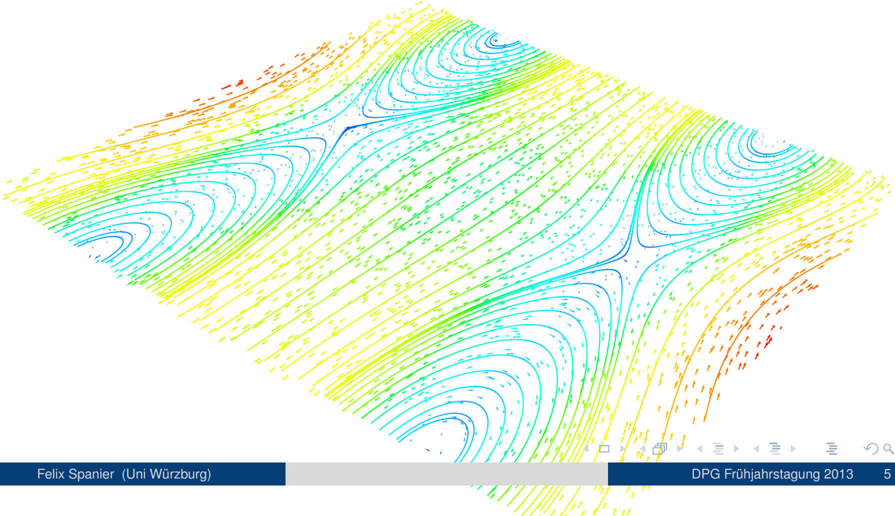
Filamentation instability



(Source: Hededal et al. 2004)

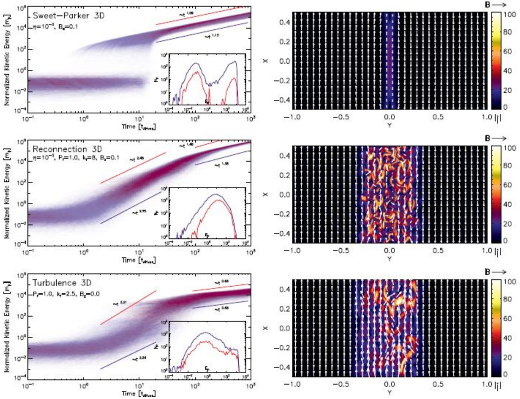
Magnetic reconnection

- Electric field in the center
- Observed in solar flares



Novel mechanisms

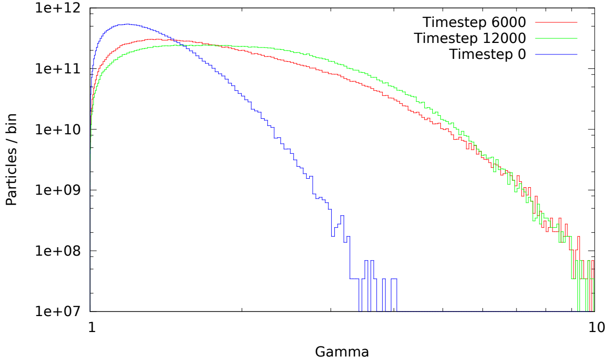
Magnetic reconnection



- Different reconnection modes
- Fast reconnection (Petschek) not well understood
- Reconnection and Fermi acceleration mix

(Source: Kowal et al. 2012)

Magnetic reconnection



- Fast electron acceleration
- Proton acceleration requires stable magnetic field configuration

Novel mechanisms

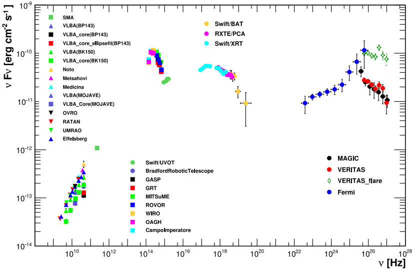
New mechanism in accelerator physics: Wakefield acceleration Based on electric fields

Source: Bussmann, 2012 $\rightarrow$ HK12.6

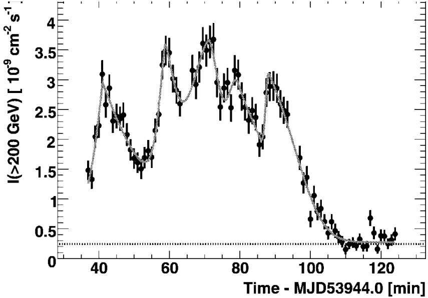
In situ observations

How to determine in situ particle spectra?
Using high energy emission of Active Galactic Nuclei, in situ particle spectra can be deduced

Multiwavelength Spectrum



Variability



AGN (Blazars?) are a candidate source for hadronic CR
The proton content of the source is yet to be determined.

Radiation modeling

Kinetic equations: acceleration zone

Fermi-I and Fermi-II process in acceleration zone

$$\partial_t n_{e^-} = \partial_\gamma \left[\left(\beta_e \gamma^2 - t_{\mathrm{a,e}}^{-1} \gamma \right) \cdot n_{e^-} \right] + \partial_\gamma \left[\left[(a+2) t_{\mathrm{a,e}} \right]^{-1} \gamma^2 \partial_\gamma n_{e^-} \right] + Q_{0,e} - t_{\mathrm{esc,e}}^{-1} n_{e^-}$$

$$\partial_t n_{p^+} = \partial_\gamma \left[\left(\beta_p \gamma^2 - t_{\mathrm{a,p}}^{-1} \gamma \right) \cdot n_{p^+} \right] + \partial_\gamma \left[\left[(a+2) t_{\mathrm{a,p}} \right]^{-1} \gamma^2 \partial_\gamma n_{p^+} \right] + Q_{0,p} - t_{\mathrm{esc,p}}^{-1} n_{p^+}$$

Kinetic equations: radiation zone

Fully-consistent radiation modeling including

- Synchrotron radiation
- Invers-Compton scattering
- Photohadronic production
- Pair processes

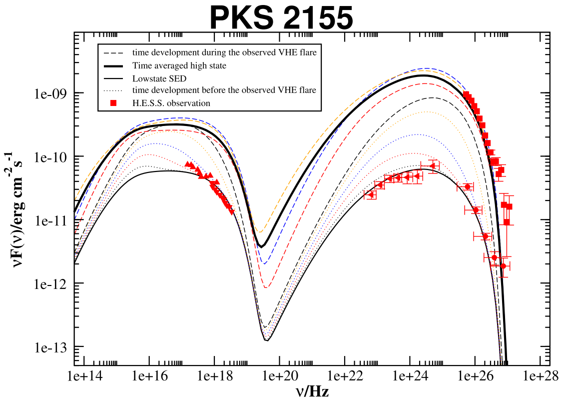
Radiation modeling

Parameters relevant to acceleration

t_{acc}	energy independent acceleration time
t_{esc}	energy independent acceleration time
a	Ratio of shock and Alfvén speed
B	Magnetic field, determines synchrotron losses

Is this sufficient to understand AGN spectra?

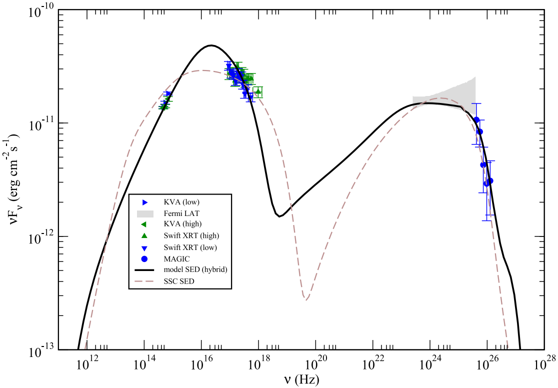
AGN results



$Q_e(\mathrm{cm}^{-3})$	$Q_p(\mathrm{cm}^{-3})$	$B(\mathrm{G})$	$R_{\mathrm{acc}}(\mathrm{cm})$	$R_{\mathrm{rad}}(\mathrm{cm})$
$8.0 \cdot 10^5$	0	1.4	$1.0 \cdot 10^{13}$	$5.0 \cdot 10^{14}$

$t_{\mathrm{acc}}/t_{\mathrm{esc}}$	a	δ	$\gamma_{0,e}$	$\gamma_{0,p}$
1.13	20	49	3300	–

1ES1011

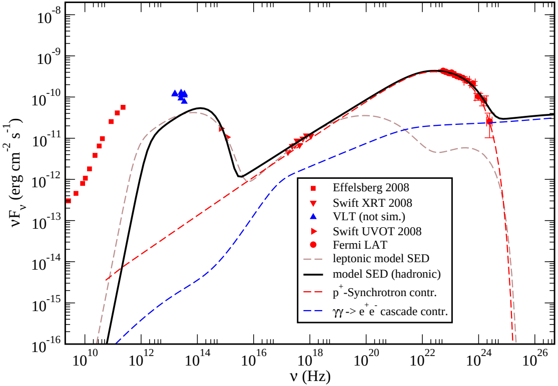


$Q_e(\mathrm{cm}^{-3})$	$Q_p(\mathrm{cm}^{-3})$	$B(\mathrm{G})$	$R_{\mathrm{acc}}(\mathrm{cm})$	$R_{\mathrm{rad}}(\mathrm{cm})$
$3.78 \cdot 10^7$	$1.55 \cdot 10^8$	8	$2.2 \cdot 10^{12}$	$1.75 \cdot 10^{15}$

$t_{\mathrm{acc}}/t_{\mathrm{esc}}$	a	δ	$\gamma_{0,e}$	$\gamma_{0,p}$
1.3	20	36	3400	$7.50 \cdot 10^4$

AGN results

3C454.3



$Q_e(\mathrm{cm}^{-3})$	$Q_p(\mathrm{cm}^{-3})$	$B(\mathrm{G})$	$R_{\mathrm{acc}}(\mathrm{cm})$	$R_{\mathrm{rad}}(\mathrm{cm})$
$3.8 \cdot 10^7$	$4.20 \cdot 10^8$	10.2	$5.0 \cdot 10^{13}$	$5.0 \cdot 10^{15}$

$t_{\mathrm{acc}}/t_{\mathrm{esc}}$	a	δ	$\gamma_{0,e}$	$\gamma_{0,p}$
1.10	5000	43	580	300

AGN parameterspace

Source	Magnetic field [G]	Spectral index	Mach number
PKS 2155	1,40	2,13	4,47
1ES1218	0,12	2,11	3,16
Mkn501	0,09	2,20	7,07
1ES2344	0,10	2,05	7,07
Mkn180	0,21	2,34	16,58
B3 2247	0,07	2,09	∞
1ES1011	8,00	2,30	4,47
PKS 0521	17,00	2,48	7,07
3C279	30,30	2,15	7,07
3C454	10,20	2,10	70,71

AGN parameterspace

Spectral index is not a problem!
Fermi-I/-II are able to explain most
Acceleration time scales?

Source	Magnetic field [G]	Spectral index	Mach number
B3 2247	0,07	2,09	∞
1ES1011	8,00	2,30	4,47
PKS 0521	17,00	2,48	7,07
3C279	30,30	2,15	7,07
3C454	10,20	2,10	70,71

AGN parameterspace

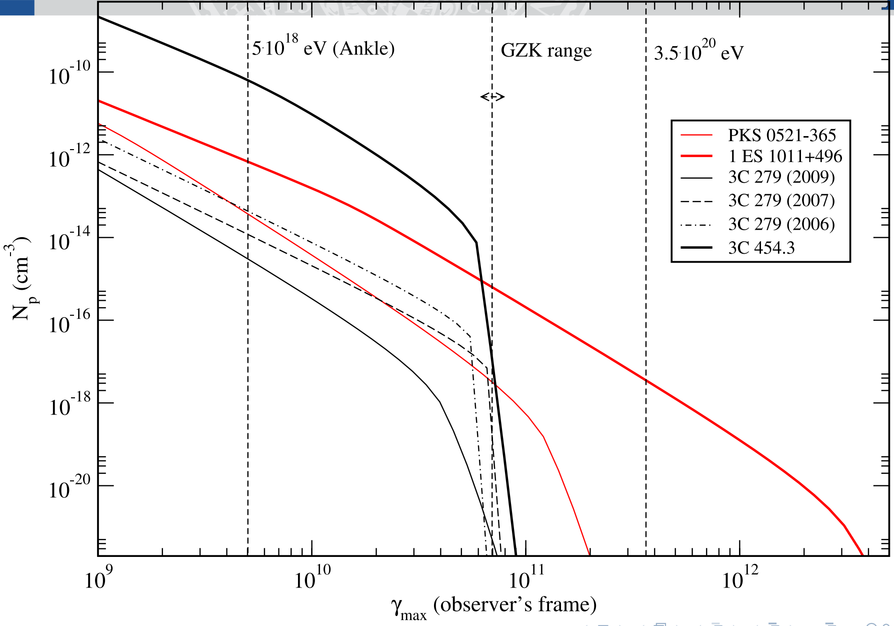
Source	$\gamma_{p,0}$	$\gamma_{e,0}$
PKS 2155	-	3300
1ES1218	-	3
Mkn501	-	12
1ES2344	-	3
Mkn180	-	7
B3 2247	-	4
1ES1011	600	3400
PKS0521	10	100
3C279	$4.25 \cdot 10^6$	155
3C454	300	580

AGN parameterspace

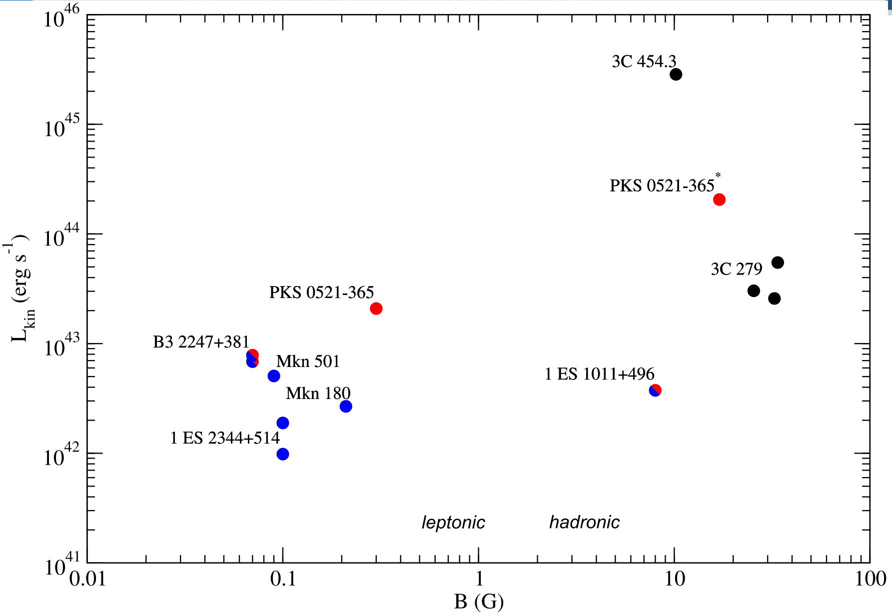
Injected luminosity is well in the Eddington Limit
Minimum Lorentz factor is a bigger problem

Source		
Mkn180	-	7
B3 2247	-	4
1ES1011	600	3400
PKS0521	10	100
3C279	$4.25 \cdot 10^6$	155
3C454	300	580

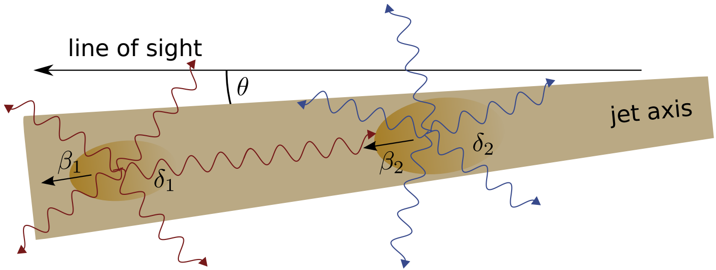
AGN CR contribution



AGN CR contribution



More modeling. . .



More advanced model: Stephan Richter, T85.3

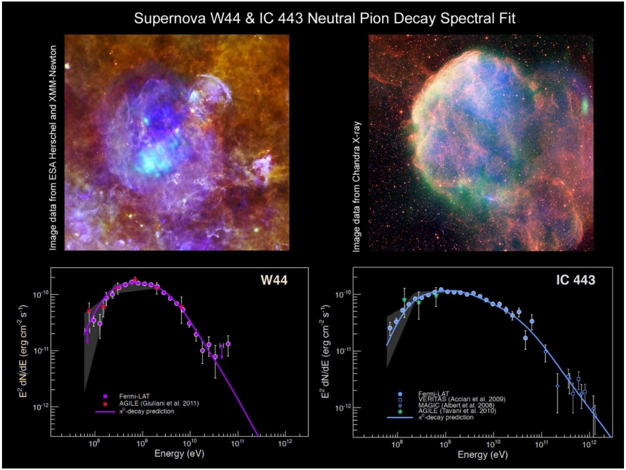
New Fermi-results

- AGN are prime candidates for UHECR
- $E < 1$ GeV CR are from solar origin
- 10^9 eV $< E < 10^{16}$ eV are most probably galactic origin

Prime candidate:
Supernova remnants

- Energy budget fits cosmic ray energy density
- Shock waves are present

New Fermi-results



New Fermi results

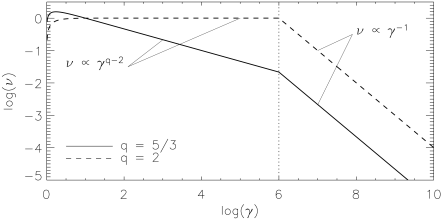
- Gamma-ray signal from SNR
- Shape fits π^0 decay extremely well
- Hint for in-situ observation of accelerated protons

Simulations

The early days

First simulations of particle acceleration with Monte Carlo codes

- Assume shock profile
- Assume scattering frequency
- Inject particles

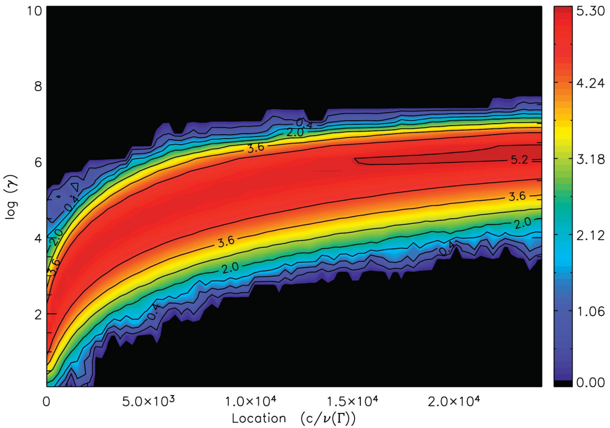


Source: Virtanen&Vainio, 2005

Perform Monte Carlo simulation. . .

The early days

...find power-law distribution



Simulations

The early days

Problems:

- No backreaction
- Is the scattering correct?

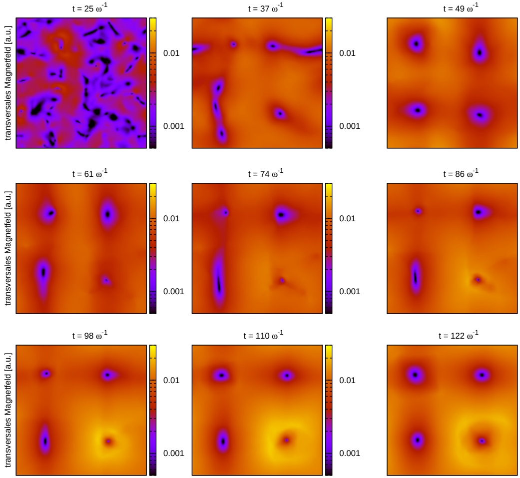
Solution is simple, beautiful and potentially unphysical!

Particle-in-Cell

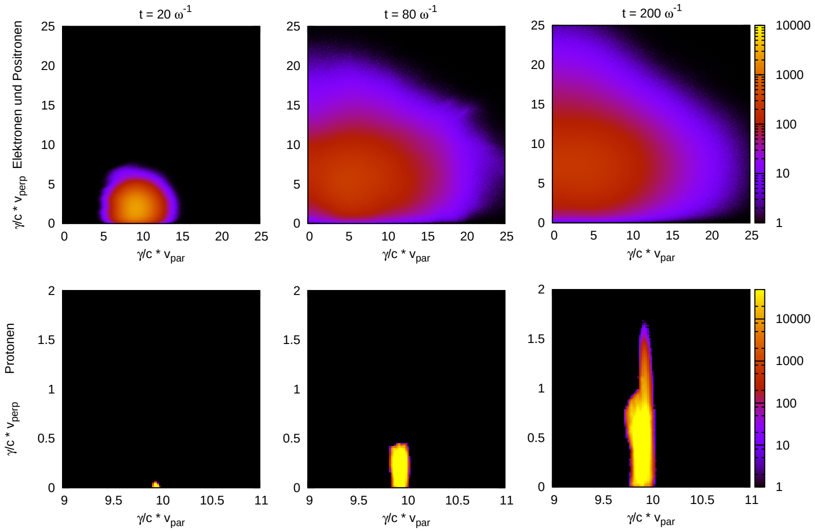
- Particle-in-Cell simulations are pretty popular
- Can Particle-in-Cell solve the question of acceleration?

Yes and No!

Filamentation stability



Filamentation stability



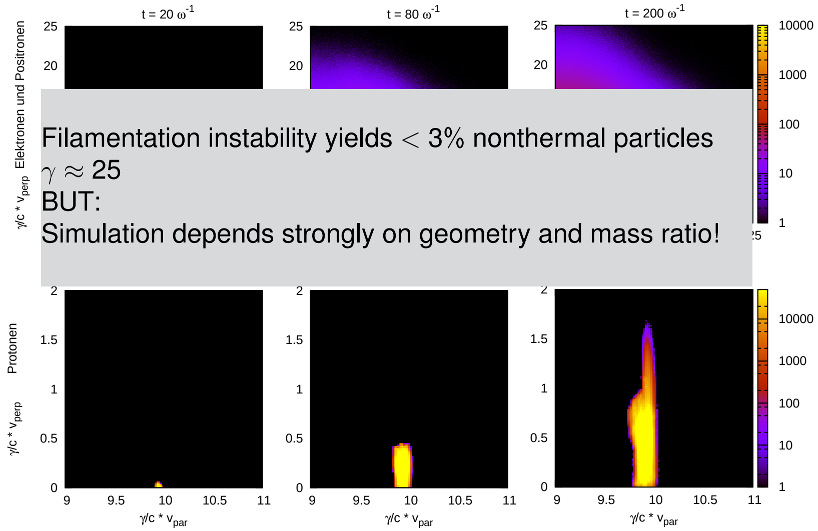
Filamentation stability

Filamentation instability yields $< 3\%$ nonthermal particles

$\gamma \approx 25$

BUT:

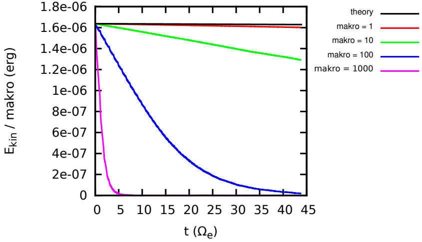
Simulation depends strongly on geometry and mass ratio!



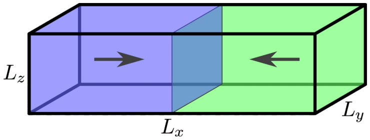
PiC and synchrotron

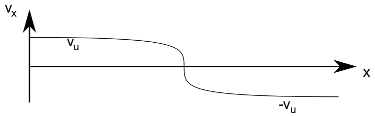
Determining acceleration time scales from PiC is complicated

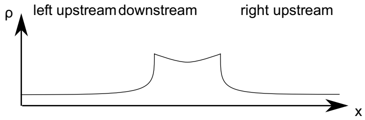
- Synchrotron losses not accounted for correctly
- Correct simulations require the resolution of gyroradii in all 3 (!) dimensions



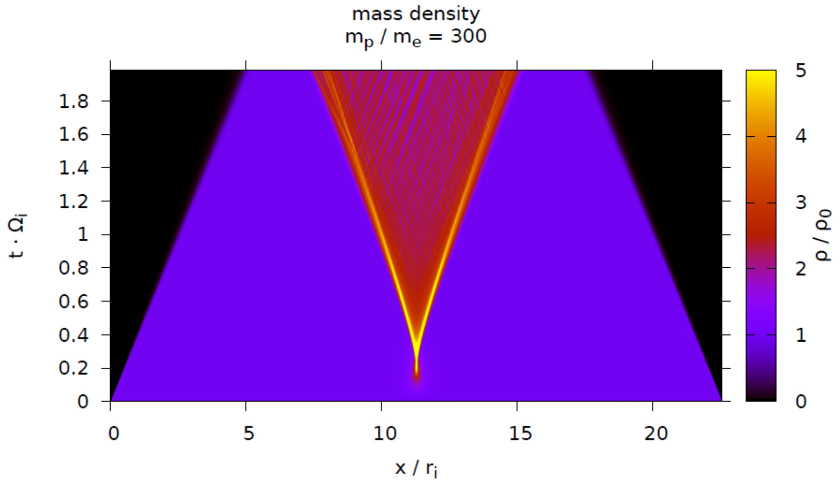
Shock acceleration



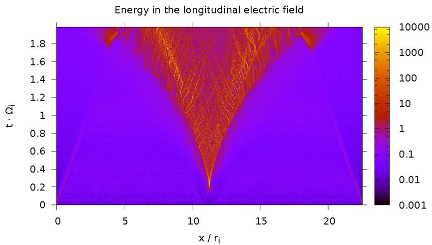


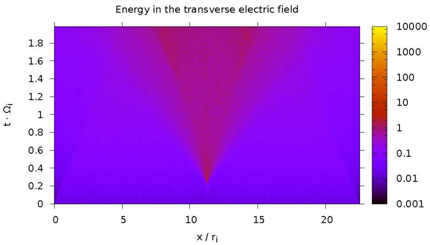


Shock acceleration



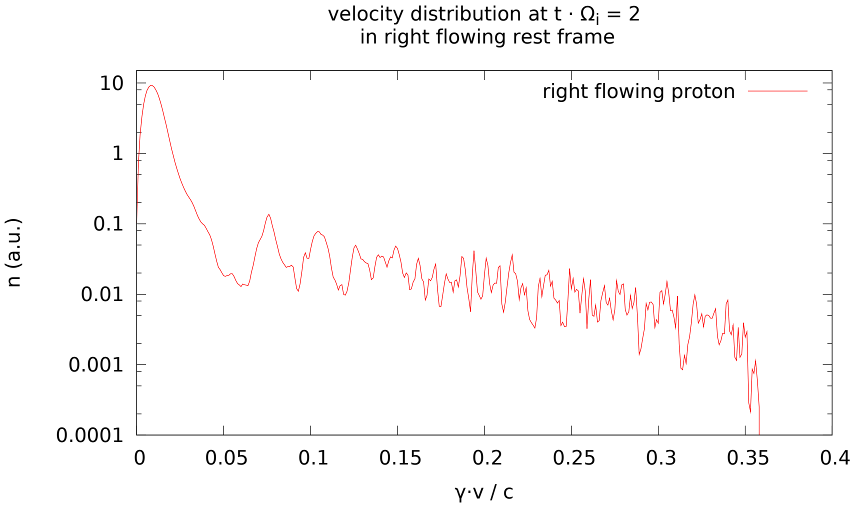
Shock acceleration



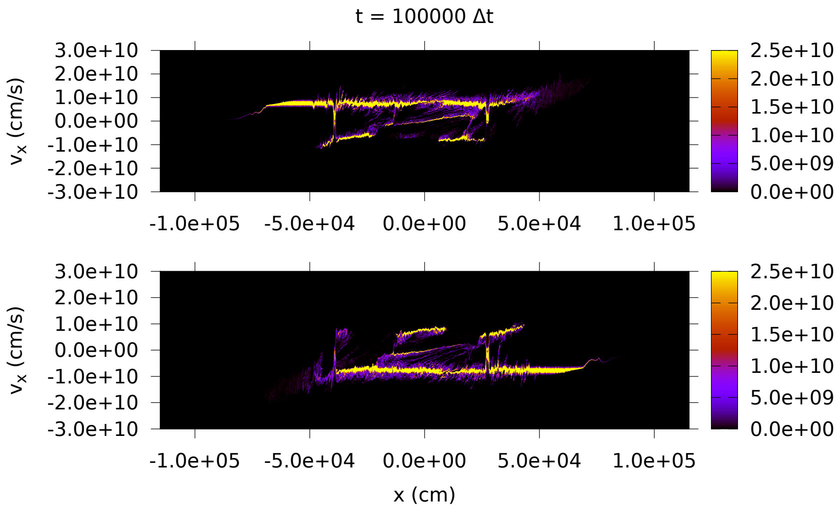


Shock shows structure in the longitudinal field
Mass density is not a uniform jump
$\Rightarrow$ Acceleration not only by pure Fermi-I!

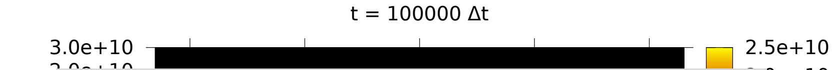
Shock acceleration



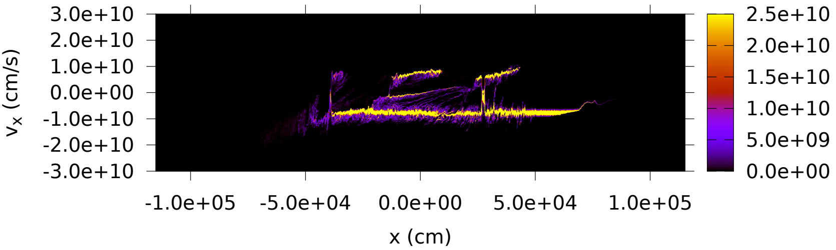
Shock acceleration



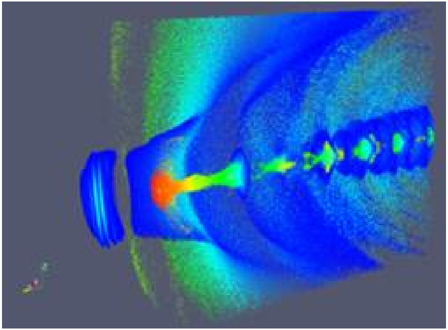
Shock acceleration



- Shock simulations are problematic
- Without artificial geometry downstream is limited
- Still: Power-law behaviour



Comparison experiment - simulation



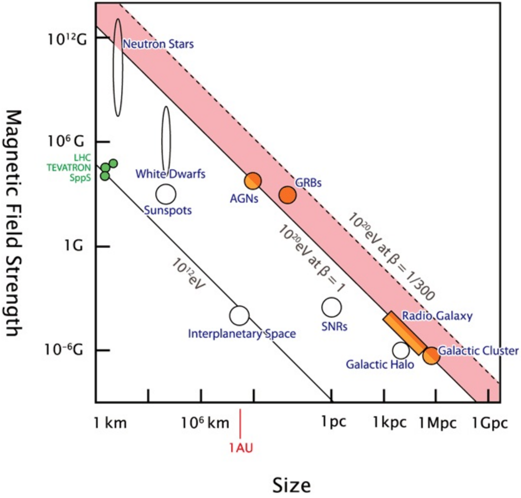
Source: Bussmann, 2012

Wakefield acceleration allows for comparison

- Lab experiments available
- System scale in PiC range

Code testing is possible, the mechanism may not be encountered in astrophysics.

Hillas criterion

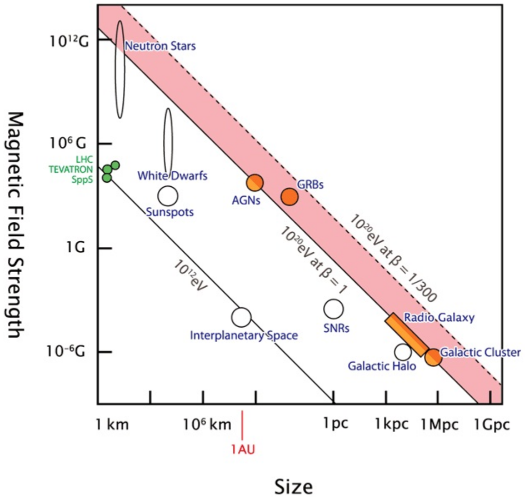


(Source: Hillas, 1984)

Classical paradigm for maximum energy
Assumptions:

- Particles are confined by magnetic field
- Gyration in ordered magnetic field

Hillas criterion



(Source: Hillas, 1984)

Does Hillas predict acceleration time $t_A \propto 1/\Omega_p$?
Hillas (1984): $t_A = v_s^2/(2c\lambda)$

Increasing acceleration time with energy yields a synchrotron problem!

Summary

- AGN are still a prime candidate for UHECR
- Fermi-I/II are a probable acceleration mechanism
- Injection problem is still a problem
- Microphysics far more complicated than simple Fermi acceleration
- What is the acceleration time scale?